

**(57) Abstract:** A microprocessor architecture (30) for executing byte compiled Java programs directly in hardware. The microprocessor targets the lower end of the embedded systems domain and features two orthogonal programming models, a Java model and a RISC model. The entities share a common data path and operate independently, although not in parallel. The microprocessor includes a combined register file in which the Java module (31) sees the elements in the register file (35) as a circular operand stack and the RISC module (33) sees the elements as a conventional register file. The integrated microprocessor architecture facilitates access to hardware-near instructions and provides powerful interrupt and instruction trapping capabilities.



- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for all designations*

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## Description

MICROPROCESSOR FOR EXECUTING  
BYTE COMPILED JAVA CODE

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## TECHNICAL FIELD

The invention relates generally to microprocessors, and more specifically to a microprocessor with a  
10 Java Virtual machine core architecture.

## BACKGROUND ART

Java is an object oriented programming language that has become a de facto standard in network programming. At the present time, Java is also beginning to be  
15 utilized in the domain of embedded systems, or systems that contain a microprocessor or a microcontroller. Some of the strong points of the Java environment like its object orientation, automatic garbage collection and run time security features can be used with success in embedded applications. However, its run time environment presents a challenge for system designers because of the resource overhead related to running the Java code in a virtual machine such as an interpreter or a just-in-time  
20 compiler. The Java binary code, called bytecode, is distributed in one or more class files. Bytecodes are the instructions of a hypothetical computer that is specifically designed for the execution of Java programs. Conventional CPUs cannot execute this bytecode and therefore execute it in a software layer called the Java Virtual machine. This machine is an abstract machine specification and no implementation guidelines are given. The Java Virtual Machine Specification is published by Sun Microsystems.

35 With reference to Fig. 17, there are basically four ways to execute a Java program on a physical computer platform. In a first method 902, the opcode is computed in a Java compiler 915 and the Java bytecode 925

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is sent to an interpreter 930 before being sent to the operating system 950 and being executed by the CPU 960. However, the interpreter 930 presents a speed penalty of a factor of five compared to executing a program compiled to native code.

A second method 903, is similar except that instead of using an interpreter, the Java bytecode is dynamically compiled into the binary format 940 for the native platform by a Just In Time (JIT) compiler 935. This process occurs inside the virtual machine and is not stored after the program has ended. The newest Java JIT technique is called HotSpot and uses a principle where bottlenecks are analyzed and recompiled during program execution. However, the JIT compiler will suffer from a memory overhead of a factor of two or three while executing the same application.

A third method 901 involves the use of cross compilers 910 to compile the Java source code into binary format 920 for the native platform. However, the platform independence is lost and the binary program cannot be executed on multiple platforms.

In a fourth method 904, a Java operating system 945 and Java processor 970 are used to execute the bytecode directly in silicon. Some Java processors have a folding mechanism, which means that several instructions are combined and executed as one. However, most Java processors will execute as an interpreter wherein each opcode is read and then the appropriate action is taken to execute the instruction.

There is no generally preferred run-time environment. Each of these environments can be used with success for different systems depending on their requirements. However, for embedded systems, the use of a Java processor (the fourth method 904) is by far the preferred technical solution if Java is to be implemented in embedded systems. In recent years, several Java virtual machines have been developed for embedded processor platforms. Most of the software solutions aim for 32 bit

processors with some 100K memory size. Additionally,  
some Java hardware processors for executing Java programs  
on silicon have also been developed. These processors,  
which support direct execution of Java instructions,  
5 implement 32 bits stack machines. Some rely on extensions to the Java binary format in order to offer features like direct addressing and bit manipulation instructions. Others do not execute Java binary codes directly, but have a very close architectural match to  
10 thereby increase performance of the virtual machine. The processors are all targeted for medium to large embedded systems. There are currently no 8 or 16 bit processors available for direct execution of Java byte compiled code, even though the eight bit processor market has been  
15 considerably larger than the 32 bit processor market.

It is the object of the present invention to provide a microprocessor for executing Java byte compiled code in hardware.

It is a further object of the present invention  
20 to provide a microprocessor architecture for executing Java that is small and power efficient enough to be a preferred solution in small to medium sized embedded applications.

## 25 SUMMARY OF THE INVENTION

The above objects have been achieved by a microprocessor for executing byte compiled Java code in hardware that includes a RISC processor, a Java module for executing a first set of Java instructions in the  
30 RISC processor, a RISC module for executing a second set of Java instructions as microcode in the RISC processor, and a data path in the RISC processor, including a register file, shared by both modules. The Java module sees the elements in the register file as a circular operand  
35 stack and the RISC module sees the plurality of elements as a register file. The microprocessor architecture is deduced from the observation that, despite Java's high semantic content instruction set, it shares a majority of

the executed instructions with instructions of a generic RISC processor. The architecture is intended to provide designers of embedded applications with an easy to integrate, small and cost effective processor solution with a well defined programming model. This results in the processor architecture embracing two programming models, making Java easy to integrate in small to medium size embedded applications.

10 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a Venn diagram showing the overlap between the Java instruction set and a typical RISC instruction set.

15 Fig. 2 is a block diagram of the architecture of the microprocessor of the present invention.

Fig. 3 is a flow chart showing a normal run sequence for the microprocessor of the Fig. 2.

Fig. 4 is a block diagram of a portion of the register file of the microprocessor of Fig. 2.

20 Fig. 5 is a block diagram of the complete register file of the microprocessor of Fig. 2.

Fig. 6 is a block diagram illustrating the interrupt handling mechanism of the microprocessor of Fig. 2.

25 Fig. 7 is a block diagram illustrating the mode transfer mechanism of the microprocessor of Fig. 2.

Fig. 8 is a block diagram illustrating the run time system in which the microprocessor of Fig. 2 would be implemented.

30 Fig. 9 is a block diagram illustrating the instruction format for the RISC portion of the microprocessor of Fig. 2.

Fig. 10 is a block diagram illustrating the addressing modes for the status registers used in the present invention.

35 Figs. 11-16 are timing diagrams illustrating the timing signals during an execution sequence of the microprocessor of Fig. 2.

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Fig. 17 is block diagram illustrating various ways to execute a Java program on a physical computer platform, as are known in the prior art.

5 Fig. 18 is a block diagram illustrating the addressing modes for the status registers of the SMILE RISC architecture.

10 Fig. 19 is a block diagram of the instruction format for the transfer and arithmetic and logic instructions of the SMILE RISC architecture used in the present invention.

Fig. 20 is a block diagram of the instruction format for the control instructions of the SMILE RISC architecture used in the present invention.

15 Fig. 21 is a block diagram of the instruction format of the LL instructions of the SMILE RISC architecture used in the present invention.

#### BEST MODE FOR CARRYING OUT THE INVENTION

20 With reference to Fig. 1, it can be seen that the Java instruction set 20 and the typical RISC instruction set 22 overlap. A Java Virtual machine instruction consists of an opcode specifying the operation to be performed, followed by zero or more operands embodying values to be performed upon. There are a total of 201  
25 opcodes in the Java Virtual machine instruction set. A significant feature of the Java Virtual machine instruction set is that a large number of instructions have a high semantic content. These instructions are difficult to implement in silicon. It is usually not feasible to  
30 execute the instructions having a high semantic content in one clock cycle, and the task of breaking them up into several less complex instructions is difficult in respect to resource allocation and timing constraints. A large part of the Java instructions are type specific and  
35 therefore, there are many instructions which have the same semantic meaning.

RISC is an abbreviation for "reduced instruction set computer". The idea behind the RISC architec-

ture is that a simpler instruction set could be executed with a higher clock frequency and more efficient pipelining, ensuring a higher throughput than in traditional stack machines. The instruction set of a RISC will of course vary from processor to processor but generally it has the following instructions: LOAD, STORE, ADD, SUB, AND, OR, SHIFT, BRANCH. In addition RISC architectures will in general include some form of bit manipulation instructions. Comparing Java's instruction set with a generic RISC instruction set, it can be found that most of the RISC instructions appear in the Java instruction set. The overlap of common instructions 25 is illustrated in the diagram of Fig. 1. The remaining instructions are divided among the RISC low level bit manipulation instructions 23 and Java's high level object creation and manipulation instructions 21. These observations establish the idea that both a RISC and a Java stack machine require approximately the same hardware resources. Additionally, a Java Virtual machine implementation in silicon needs to support instructions for bit manipulation, direct memory addressing, and trapping of complex opcodes. Also, the most frequently executed instructions in both architectures are the load/store instructions. In both architectures, they have the same semantic content. Implemented on silicon, these instructions could share the same hardware resources. These observations on the nature of the two instruction sets leads to the microprocessor architecture of the present invention.

With reference to Fig. 2, the microprocessor 30 of the present invention includes a Java control unit 31 and a RISC control unit 33 which share the same data path. The two control units 31, 33 operate independently but cannot operate simultaneously. In other words, the two virtual processors share one data path but, although they operate independently, they do not operate in parallel. The processor 30 does not rely on translations or extensions to the Java binary format like other Java



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processors, but offers two orthogonal programming models. The microprocessor 30 is in principle a von-Neuman architecture, but it can easily be expanded to a Harvard architecture with a separate data and instruction bus. The

5 microprocessor includes a register file 35 having a status register 32 and a program counter 34. The register file is connected to the data bus 40. An arithmetic logic unit (ALU) 42 is connected to the register file 35 and the output of the ALU is supplied to the data bus 40.

10 This is partly because a large part of the critical path goes through the ALU and partly because this is one of the larger modules in an embedded microprocessor. The minimum ALU implementation should perform the operations: ADD, SUB, AND, OR, XOR, MOVE, SET, CLEAR, SHIFT, and

15 ROTATE. The outputs of the register file 35 and the program counter 34 are processed through an adder 36 to an address multiplexer 37. The address multiplexer 37 is also connected to the address bus 41. An instruction fetch decoder 39 receives a signal from the data bus 40

20 and provides an output to the stack control unit 38.

With reference to Fig. 3, the microprocessor first powers up in the RISC mode of operation in order for the initialization code to execute. After the initialization 52, the microprocessor switches to Java mode

25 53 and starts executing the Java program 54. The microprocessor operates in Java mode until one of three events occurs: an interrupt 59, an unimplemented Java instruction 60, or a designated Java opcode for switching back to RISC mode 58. If any of these events occur, the processor will jump to a pre-defined address and switch to

30 RISC mode 55 and in this way handle the event. Upon finishing the RISC routine 56, the processor will switch back to Java mode 57 and continue to execute the Java code at the point where it left off.

35 Thus, the Java model is able to execute the Java parts of the program. Such parts may be network capabilities or algorithms which are already implemented in a company's software library, and constitute modules

of legacy software for reuse. The RISC model aids in execution of the Java code by executing complex instructions as microcode. It also provides a flexible hardware interface which can be used to, for example, control  
5 highly specialized peripheral devices like sensors and actuators. In order to be compatible with the Java Virtual machine specification, all Java instructions need to be implemented. However, in an embedded processor targeted for small to medium applications, several of the  
10 number formats supported by the Java Virtual machine are excessive. For instance, there are few processors in this segment that offer floating point units. Several of Java's more complex instructions have to be trapped and executed as microcode. Which instructions to trap and  
15 which to implement directly into hardware is usually an implementation specific issue decided by the designer. Additionally, which RISC instruction set to use depends on the RISC model chosen, as the present invention can also be used with other types of RISC architectures in  
20 addition to the RISC architectural described herein.

A key architectural element in the proposed microprocessor architecture is the register file. This module has the function of a push-pop stack in Java mode and as a conventional load/store register file in RISC  
25 mode. This is also the module which allows the two virtual processors to communicate. With reference to Fig. 4, the RISC part of the architecture 71 sees a register file with N registers, and the RISC architecture interfaces the registers with the data memory through  
30 load/store instructions 72, 73, 74. The program counter and status register are included in the register file. In order to preserve orthogonality, these special registers are accessible like any other register. The Java control unit 61 sees the same register file as a push-pop  
35 stack with  $M = N/2$  elements. Data is pushed 62 into the register stack and is popped 63 out of the register stack to the Java control unit. Fig. 4 shows half of the register file as it is seen from the RISC and Java modes.

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The registers 80, 81, 82 are seen by both the Java control unit 61 and the RISC portion of the circuit 71. The remaining N/2 registers are used for, among other things, the program counter, status register, scratch registers and stack control registers. The stack is implemented as a circular stack and the stack sizes required are relatively small. The stack size is scalable, and the number of stack elements is left as an implementation specific issue. A stack overflow/underflow can be copied out in the memory 83 through an overflow/underflow mechanism. Possible stack overflow/underflow mechanisms can also be developed in a case-by-case manner.

With reference to Fig. 5, the complete register file 90 is shown. The RISC module can read and write from all the registers and there are no hardware limitations on which registers the RISC module can access. The verification that the RISC module does not overwrite a special register during program execution is done in the software layer. If the programmer wants to use one of the special registers as a temporary memory, it will have to be stored on the RISC module stack if the value in this register needs to be recovered later during the execution. As shown in Fig. 5, the complete RISC register file 90 includes the Java operand stack 91 which includes a plurality of registers 92, 93, 94, 95, as was described with reference to Fig. 4. The RISC registers 90 also includes a plurality of special registers. The special registers include a program counter 106, a program counter base 105, a constant pool base address 107, a local variable base address 104, a Java stack pointer 103, a status register 101, and a RISC stack pointer 102. Most of these register functions are self-explanatory. The program counter base register 105 is used by the Java processor. When a new method is invoked, the Java module's program counter is set to zero. The program counter base register stores the address where this method is invoked. On the address bus, this register is added with the program counter in order to fetch instructions from

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the correct place in the program memory. The local variable base address register 104 performs a similar function. It stores the base address for the local variable in a Java method. These registers could of been chosen  
5 to reside outside the register file 90. However, it represents an advantage to be able to have these registers inside the register file since the register can be reached by any RISC instruction, rather than having to implement special instructions to operate on special  
10 registers. The Java stack pointer 103 keeps track of the location of the top of the Java operand stack, thus keeps track of the particular register of the M registers from which the operand is going to be fetched or to which the operand is going to be written. The RISC stack pointer  
15 102 points to a place in memory where the RISC can store variables temporarily if the register file is full.

The virtual processors communicate through the register file. The RISC unit executes, amongst others, complex Java instructions. These small RISC programs  
20 have to fetch their operands from the top of the Java operand stack and place the results back to the top of the Java operand stack, and at the same time make sure that the Java stack pointer is incremented or decremented depending on the operation performed. This presents a  
25 problem since the RISC instruction format will only handle static registers. The problem is solved by setting and clearing two status bits in the status register. Each of the status bits controls whether the source (X) or the destination (Y) operand are to be fetched from the  
30 register indicated in the instruction or whether the register number is to be dynamically read from the Java stack pointer register. The RISC program which replaces a Java instruction has to set and clear these bits at the appropriate time. By setting the two bits in the register  
35 file, the RISC processor can use the content of the top of stack register as an argument for which register to access.

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With reference to Fig. 7, the implementation of the mode transfer mechanism of the microprocessor is shown. The Java control 120 and RISC control 122 modules are connected to a multiplexer 124 which produces the control lines 130 to the data path. The status register 126 in the register file contains a control bit 128 which is supplied to the Java control module 120, and the RISC control module 122. The control bit 128 also serves as the control input to the multiplexer 124. The control bit determines which of the control units, Java control unit 120 or RISC control unit 122, is in operation. Control is transferred at a predefined state in both control modules. Control is therefore transferred synchronously where both machines will be in the same defined state.

The Java Virtual machine specification does not describe the concept of interrupts. Therefore interrupts are handled by default by the RISC module. With reference to Fig. 6, the interrupt handling mechanism is shown. In general, when an interrupt occurs, the processor checks that the implementation specific conditions, like specific flags, are true before jumping to a predefined address and switching to RISC mode. Then, the return address is stored on top of the RISC stack. In Fig. 6, the jump address (0x63) 112 is shown to be stored at the predefined address (0xaf) 111. At this predefined address, the jump address is read and an appropriate branch instruction to the new address is performed. Execution continues at this new address in RISC mode. To return to normal program execution, the processor executes the RISC instruction "Return from Interrupt" where the return address is popped off the top of the RISC stack.

The instruction trapping mechanism involves steps similar to the interrupt mechanism. When an unimplemented instruction occurs; the JAVA control module detects this and the return address is stored on the top of the stack. Then, the processor switches to RISC mode

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and fetches a jump address from a predefined location in the memory. The RISC module then continues execution at the address fetched in the last step. Having the trapping mechanism be similar to the interrupt mechanism achieves maximum flexibility since only the first jump address is predefined in the design. This will enable the software linker to optimally plan the memory usage by only linking the RISC routines for the Java opcodes actually present in the program, thus saving precious memory space. The RISC routine should end by popping the program counter off the top of the stack and saving it in the program counter register. This will ensure that the Java program continues at the correct place. Additionally, the microprocessor has a stack overflow/underflow handling mechanism. This mechanism in the Java push-pop stack can be implemented by reusing existing logic for instruction trapping. When an overflow occurs, the processor traps the overflow flag and jumps to a predefined address where it finds a jump vector to the software procedure that will handle the overflow/underflow condition.

With reference to Fig. 8, a typical run-time environment for a system with this processor concept is shown. A developer can compile Java source code 141 in an ordinary Java compiler 142 and end up with Java class files 144. If the processor accommodates an operating system with a file loader and an automatic memory management system, the rest of this process can occur dynamically and automatically. However, small embedded systems often do not need an operating system and then the rest of this process must be done manually in the sense that a memory image of the program has to be created on an external platform. The Java class files 144 have to be parsed through a linker 148. The program run through the linker will verify that the class file doesn't contain any illegal opcodes, modify codes or operands depending on instrumentation solutions, link the application with the specified Java class libraries 145, link an assembly

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code to the RISC part 143, set up a heap area, set up  
branch and jump addresses, and make a memory map. The  
output from the linker will be a memory image which can  
be transferred to the ROM or flash memory 151 in the  
5 embedded system 152. Much of the purpose of making a  
Java processor is that the programmer should be able to  
use the Java programming language as unconstrained as  
possible. However, in this case, only supported types  
can be used and only a limited run-time library will be  
10 available. These constraints are, however, not limiting  
for the use of Java's main features.

The Java Virtual machine specification contains  
201 instructions, many of them type specific. The number  
of instructions hardware implemented, and the number of  
15 instructions trapped, depends on the RISC architecture  
that is used. Other types of RISC architectures will  
have an effect on the number of instructions hardware  
implemented and trapped. The following instructions were  
not hardware implemented in the preferred embodiment of  
20 the present invention since these instructions are not  
considered as important in a small embedded processor:  
all instructions of type "float", all instructions of  
type "double", and all instructions of type "long". This  
eliminates approximately 90 instructions from the 201  
25 possible Java instructions. Of the remaining instruc-  
tions, 68 instructions are implemented in the Java Vir-  
tual machine and 43 instructions are trapped and are  
executed as RISC routines. The instructions that are  
trapped and executed as RISC routines are noted below in  
30 Table 1.

Table 1

Opcode	Mnemonics	Opcode	Mnemonics	Opcode	Mnemonics
18	ldc	104	imul	182	invokevirtual
46	iaload	108	idiv	183	invokespecial
50	aaload	112	irem	184	invokestatic
51	baload	170	tableswitch	185	invokeinterface

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5	52	caload	171	lookupswitch	187	new
	53	saload	172	ireturn	188	newarray
	79	iastore	173	lreturn	189	anewarray
	83	aastore	176	areturn	190	arraylength
	84	bastore	177	return	191	athrow
	85	castore	178	getstatic	192	checkcast
	86	sastore	179	putstatic	193	instanceof
10	90	dup_x1	180	getfield	194	monitorenter
	91	dup_x2	181	putfield	195	monitorexit
	92	dup2			197	multianewarray
	93	dup2_x1				
	94	dup2_x2				

With these implementation choices, approximately 70% of the executed instructions will be executed in the processor directly, while approximately 30% will be trapped and executed as RISC programs. These percentages are derived from dynamic measurements.

For the RISC architecture, the SMILE RISC architecture was chosen. SMILE is an abbreviation for "Scalable Microcontroller Library Element" and was developed by Andrew K. Betts at University College London and is described in several publications, including:

A.K. Betts, I. Bolsens, E. Sicard, M. Renaudin, and A. Johnstone, SMILE, a scalable microcontroller library element, In *Proceedings of Euromicro*, 1993;

A.K. Betts, I. Bolsens, E. Sicard, M. Renaudin, and A. Johnstone, SMILE, a scalable microcontroller library element, *Microprocessors and Microprogramming*, 39:259-262, 1994; and

A.K. Betts, SMILE, scalable microcontroller library element, functional specification, V.6. Technical report, University College London, 1993.



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The essential details of the SMILE specification are described below at the end of this section. SMILE is targeted for small embedded systems and has certain scalability qualities. The virtual RISC of the present invention implements a modified SMILE instruction set, except that the instructions format was slightly changed in order to accommodate 32 register addressing as is shown in Fig. 9. Additionally, the status registers in the present invention have been modified from the standard SMILE specification registers that are discussed with reference to Fig. 18 below. The status registers of the present invention are shown in Fig. 10 and include a read/write register SR1 180, and a second register SR2 having a read only portion 185 and a write only portion 188. The read/write register SR1 180 includes the Java flag 183, discussed above with reference to Fig. 6, and also includes the Rx 182 and Ry 181 flags, which will be described below with reference to Fig. 14. The remaining bits in the register are the same as in the SMILE specification, which is described below with reference to Figs. 18-21. Additionally, the range of some instructions were expanded, all registers are defined as type "long", the register scaling parameters have been changed, and some new instructions were added. The new instructions are: return from Java trap (RJ), RISC to Java control transfer (R2J), shift Java alignment left (SJL), and shift Java alignment right (SJR). The semantics of these new instructions are described below with reference to Figs. 11-16.

The signals shown in each of Figs. 11-16 are the reset signal 241, the clock signal 242, the Java instruction register 243, the RISC instruction register 244, the Java flag 245, the data bus 246, the program counter 247, the address bus 248, the Java Stack pointer 249 and the actual time 250. Also, the instruction sequences 201-206 for each time period are shown.

In Fig. 11, the first ten clock cycles are shown. After the reset signal 241 goes inactive, the

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processor is in RISC mode and initializes by executing the instruction it reads at address 0x0000. It then executes a series of load instructions to initialize the special registers Stack Pointer, Local Variable Base Address, and Program Counter Base Address. The initialization described is valid for a reset routine. A JAVA call would include initializing only the Local Variable Base Address and the Program Counter Base Address. In addition, the Constant Pool Base Address would have to be initialized if a new class was called. At time 95, the processor executes the instruction R2J which is equivalent to setting bit six in the status register.

After the instruction R2J is executed, the processor switches to Java mode in the next clock cycle. The transfer of control is seamless as shown in Fig. 12. Note that the Java flag signal 245 is set high at time 105 and that the program counter 247 is set to zero as all Java methods start at zero. The address on the address-bus 248 is the sum of the Program Counter and the Program Counter Base Address registers.

As shown in Fig. 13, at time 215, the Java instruction "istore <index>" is executed ("36" in Java instruction register 243). This instruction pops a variable of "Top of Stack" and stores it into a local variable at address "<index>". It can be seen that the number "0" (see databus 246) is stored into address "184" on the address bus 248. The address is calculated from LV base address plus PC base address plus the operand <index> which belonged to the instruction. Here <index> was 0x4 thus the address is  $0x69 + 0x4B + 0x04 = 0xB8 = 184$ . In addition, it can be observed that the Top of Stack pointer 249, which points to the register that is currently "Top of Stack", is decremented as the number is popped off the stack.

Execution of "istore" at time 215 takes two clock cycles as shown in Fig. 13. Later in the same figure, an "istore" is executed again at time 245. This

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time, the alignment of the instruction in memory forces the opcode and the operand to be read on different clock cycles. The execution of this instruction is thus done in three clock cycles.

5           At time 315 in Fig. 14, the Java control module reaches the unimplemented instruction "newarray". This instruction is trapped. The trap sequence takes four clock cycles as described above. At the 350, the end of the top sequence, the Java flag goes low. The processor  
10       now starts executing the instruction newarray as a RISC routine. The instruction should initialize an array and return the start address for the array. The RISC instructions SJL and SJR are move instructions to handle the alignment of the Java opcodes in the memory.

15           With reference to Fig. 15, the Java stack pointer has a post-increment function. At time 435 the stack pointer is decremented in order for the RISC to access the correct register. Next, at time 455 in Fig. 14, the RX flag is set in the status register. This  
20       means that the RISC reads the Java Stack Pointer register to determine the "Top of Stack" and uses this as the RX register in the next instructions. This is what happens at time 465 where a constant is loaded into "Top of Stack". This constant is the return value from the RISC  
25       routine returning the address of the newly created array. In this example, the array is static and the return value is therefore loaded as a constant.

          Finally, the Java stack pointer is incremented again at time 495 before the RISC returns control to the  
30       Java module again at time 515 in Fig. 16. The processor then continues to execute in Java mode.

#### Smile Specification

          As discussed above, the SMILE RISC specification was chosen in the implementation of the present  
35       invention. The specification of the SMILE implementation used in the present invention is described herein.

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The SMILE microcontroller must satisfy the following requirements: scalable size, design simplicity, moderate speed and moderate code efficiency. SMILE would typically be part of a larger system including timers, memory and some form of analog interface. The design will follow RISC principles whenever this is practical and relevant. The compact instruction set (24 instructions) will have the following features:

10 \* Uniformity: Every type of operation will be applicable to all processor registers and all combinations of processor registers in the same way (with the exception of some operations on the status register), and all instructions will be conditioned.

15 \* Completeness: The instruction set will be complete with respect to the application area of embedded control.

20 \* Orthogonality: The instruction set will be orthogonal, and there will be no undecoded instructions.

25 \* Parameterization & Scalability: as the user may be in a position to modify the core hardware, the design will be parameterized. It will also be possible to scale the design according to the width of the memory, with the smallest width being 4 bits. Functionality will degrade gracefully as the memory width is reduced. Finally, expansion of the instruction set will be allowed through the addition of application specific instructions.

30

The following three parameters will be specified in order to characterize a particular version of SMILE:

35	WSR	Width of short register in bits	WSR $\geq 4$
	WIR	Width of instruction register	WIR $\geq 12$
	NRE	Number of registers	NRE $\geq 8$

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The following restrictions apply to the choice of the above parameters. NRE is a power of 2.

$$6 \leq \text{WIR} - 2\log_2 (\text{NRE}) \leq 10$$

5

SMILE versions will be specified as SMILEWSR\_WIR\_NRE.  
The following parameters are derived from the above:

	WRF	Width of register field in insn	$2 \cdot \log_2 (\text{NRE})$
10	WCF	Width of condn. field in insn.	$\text{WIR} - \text{WRF} - 6$
	NIS	Number of segs in insn reg	$(\text{WIR} + \text{WSR} - 1) / \text{WSR}$ (integer truncated)
	WLR	Width of long registers	$2 \cdot \text{WSR}$
	WIF	Width of instruction field	$= 3$
15	WAF	Width of address-mode fields	$= 3$
	NSR	Number of short registers	$2^{(\text{WRD}/2)} / 2$
	NLR	Number of long registers	NSR
	NPA	Number of process addresses	$2^{\text{WLR}}$
	NTA	Number of total addresses	$2^{2\text{WLR}}$

20

The processor switches between processes on interrupt. Each process will see a set of NSR + NLR General Purpose Registers. Register L[NLR-1] will be the program counter, PC.

25

Register L[0] will be the stack pointer, SP. Register S[NSR-1] will be the Interrupt Control and Status Register, SR. Registers designated "local" are stacked on interrupt. The local registers are to be the Program Counter, PC (L[NLR-1]), the Status Register, SR ((S[NSR-1])), and the Memory Configuration Register, MCR. All other registers will be designated "global". When short registers are combined in an operation with long registers, or they are used as an address, they are zero-extended. This allows the short registers to be used to point to the first page ( $2^{\text{WSR}}$  locations) of data memory.

30

35 Status information is held in two registers, SR1 and SR2, as defined by the following diagram. The addressing modes used to access this information are shown in Fig. 18 and are described below.

-20-

With reference to Fig. 18, the status bits are as follows:

SR1 (read/write), 411:

5    U    User bit - no dedicated function  
      N    Negative flag  
      V    Overflow flag  
      Z    Zero flag  
      C    Carry flag

10

SR2 (read only), 421:

     M    =Z + Cbar (convenient access to condition "lower or  
           same")  
      I    =Z + L (convenient access to condition "less or  
 15        equal")  
      L    =N^V (convenient access to condition "less")  
      E    interrupts enabled when this is set

SR2 (write only), 422:

20    S    holds results of TB & FB instructions set to 1 by  
           other instructions  
      K    set to 1 unless instruction explicitly clears  
      P    set to 1 unless instruction explicitly clears  
      E    as above

25

For this version of the specification, data and instruction memories will be identical. Memory accesses that use the program counter as a pointer will read instruction memory, while all others will read or write data memory (nb, immediate constants are therefore in instruction memory). Accesses to instruction memory are read-only. Memory will be accessed as shorts or longs, depending on the operation. The high and low parts of longs will be ordered according to the little endian

30

35 convention.

The instruction set is noted in Table 2 below:

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TABLE 2

	<u>Transfers</u>			<u>Operation</u>	<u>Flags</u>
5	LD	Ax,Ay	load	$Ax \leftarrow Ay$	SZ
	ST	Ax,Ay	store	$Ay \leftarrow Ax$	SZ
<u>Arithmetic and Logical</u>					
10	AD	Ax,Ay	add	$Ax \leftarrow Ax + Ay + C'Kbar$	SCZNV
	SU	Ax,Ay	subtract	$Ax \leftarrow Ax - Ay - Cbar'Kbar$	SCZNV
	AN	Ax,Ay	and	$Ax \wedge Ay$	SZN
	OR	Ax,Ay	or	$Ax \vee Ay$	SZN
	EO	Ax,Ay	exclusive or	$Ax \wedge Ay$	SZN
<u>Manipulation and Test</u>					
15	TB	Ax,n	test bit n(0..3) for True	$S \leftarrow Ax \cdot 2^n$	SZ
	FB	Ax,n	test bit n(0..3) for False	$S \leftarrow \neg (Ax \cdot 2^n)$	SZ
	SB	Ax,n	set bit n(0..3)	$Ax \leftarrow Ax + 2^n$	SZ
	CB	Ax,n	clear bit n(0..3)	$Ax \leftarrow Ax \cdot (2^n)bar$	SZ
20	SL	Ax,n	shift left n(1,2,4)	$Ax \leftarrow Ax \ll n$ (shifting in 0)	SCZ
	SR	Ax,n	shift right n(1,2,4)	$Ax \leftarrow Ax \gg n$ (shifting in 0)	SCZ
	SA	Ax,n	shift arith. n(1,2)	$Ax \leftarrow Ax \gg n$ (shifting in ms_bit)	SCZ
	RL	Ax,n	rotate left n(1,2,4)	$Ax \leftarrow Ax \ll n$ (shifting in msb)	SCZ
	RR	Ax,n	rotate right N(1,2,4)	$Ax \leftarrow Ax \gg n$ (shifting in lsb)	SCZ
	RC	Ax,d	rotate carry (d=L/R)	Ax rotated 1 bit L/R through carry	SCZ
<u>Control</u>					
30	BR	<offset>	branch	$PC \leftarrow PC + (\text{signed}) \text{ offset}$	S
	JS	<laddr>	jump subroutine	stack PS, $PC \leftarrow \text{<laddr>}$	S
	JI	<daddr>	jump with int.	see text	S
	RI		return from int.	see text	S
<u>Version Specific</u>					
35	LL	Ax,n	load literal n	$Ax \leftarrow n$	SZ
	VS	n	vectored subroutine	see text	S
	FN	n, [<arg>]	function n	not specified	S
nb. abbreviations:					
40	<offset>		signed offset, length WSR		
	<laddr>		absolute address, length WLR		
	<dladdr>		absolute address, length 2*WLR (for PC + MCR)		
	<constant>		immediate constant value		
	<arg>		unspecified optional parameter to pass to function		

The following are attributes of the instruction set shown in Table 2. ST x,y is not an allowed instruction. Status bits K and P are affected by all instructions. All instructions may have a further field <cdn>

-22-

added to specify a condition (not shown in above table).  
 If this is not specified, then the default condition  
 tests the S bit. This bit is set by all instructions  
 except TB and FB, which sets or clears it depending on  
 5 the result of the test. Instructions are always exe-  
 cuted, and the appropriate status bits set. However, the  
 results are only stored if <cdn> is true. The y result  
 is always stored in pre-decrement and post-increment  
 instructions. The VS instruction is identical to the JS  
 10 instruction, except that the jump address is not required  
 to follow the instruction. Instead, this address is  
 fetched from an address table that is internal to the  
 SMILE core, and the index used to retrieve the appropri-  
 ate address is n - the VS argument. This instruction  
 15 therefore allows a subroutine jump where the destination  
 of the jump is coded into the instruction itself.

The addressing modes for the Ax operand are  
 defined as follows:

20	<u>addressing mode</u>	<u>&lt;operand&gt;</u>	<u>effective address for Ax</u>
	simple	x	x
	indirect (xid)	(x)	M[x]

The addressing modes for the Ay operand are defined as  
 25 follows:

	<u>addressing mode</u>	<u>&lt;operand&gt;</u>	<u>effective address for Ay</u>
	register	y	y
	pre-decr	-(y)	M[y-1], y decremented
30	post-incr	(y)+	M[y], y incremented
	displacement	<disp>(y)	M[<disp>+y]
	immediate	<constant>	M[PC]

35 For displacement mode, the displacement follows the in-  
 struction in memory. For post-incr and pre-decr modes,  
 the increment/decrement value =1 if the register in the x  
 field is short, else =2. <disp> is a displacement, the  
 same width as y. It is added to y and then the result



zero-extended so that, when y is short, the mode can be used to access any element of the first page of memory. The arguments Ax and Ay are always treated as having the same width as register x. If the y addressing mode is "register" and y is longer than x, then the least significant part of y is used for the operation. If the y addressing mode is "register" and y is shorter than x, then y is zero-extended for the operation. The status register address has a special logical interpretation:

10

<u>Instruction argument</u>	<u>Effective argument</u>
Ax = SR	Ay = SR1
Ax = (SR)	Ay = SR2
Ay = SR	Ay = SR1
15 Ay = -(SR)	Ay = ~(SR)
Ay = (SR)+	Ay = (SR)+
Ay = <disp>(SR)	Ay = M[<disp>]

20

S.K and Y are set to one every instruction, unless otherwise specified.

Table 3 defines the status calculations, where: Ax\_result denotes the result of the calculation for Ax which, in fact, will only be stored if the condition corresponding to the operation is met. Ay\_result denotes the result of the calculation of the effective address for the y field in pre-decrement, post-increment and displacement addressing modes.

25

TABLE 3

30

Transfers

LD	Ax,Ay	Z = if (Ax_result == 0 ? 1:0)
ST	Ax,Ay	Z = if (Ay_result == 0 ? 1:0)

35

Arithmetic and Logical

AD	Ax,Ay	C = if (carry out of Ax_result ? 1:0)
		Z = if (Ax_result == 0 ? 1:0)
		N = msbit of Ax_result
SU	Ax,Ay	C = if (borrow from Ax_result ? 0:1)
40		Z = if (Ax_result == 0 ? 1:0)

-24-

			V = if (overflow of Ax_result ? 1:0)
			N = msbit of Ax_result
	AN	Ax,Ay	Z = if (Ax_result == 0 ? 1:0)
			N = msbit of Ax_result
5	OR	Ax,Ay	Z = if (Ax_result == 0 ? 1:0)
			N = msbit of Ax-result
	EO	Ax,Ay	Z = if (Ax_result == 0 ? 1:0)
			N = msbit of Ax_result
10	<u>Manipulation and Test</u>		
	TB	Ax,n	S = Ax·2 <sup>n</sup>
			Z = Ax·2 <sup>n</sup>
	FB	Ax,n	S = ! (Ax·2 <sup>n</sup> )
			Z = ! (Ax·2 <sup>n</sup> )
15	SB	Ax,n	Z = if(Ax_result == 0 ? 1:0)
	CB	Ax,n	Z = if(Ax_result == 0 ? 1:0)
	SL	Ax,n	C = if(carry out of Ax_result ? 1:0)
			Z = if(Ax_result == 0 ? 1:0)
	SR	Ax,n	C = if(carry out of Ax_result ? 1:0)
20			Z = if(Ax_result == 0 ? 1:0)
	SA	Ax,n	C = if(carry out of Ax_result ? 1:0)
			Z = if(Ax_result == 0 ? 1:0)
	RL	Ax,n	C = if(carry out of Ax_result ? 1:0)
			Z = if(Ax_result == 0 ? 1:0)
25	RR	Ax,n	C = if(carry out of Ax_result ? 1:0)
			Z = if(Ax_result == 0 ? 1:0)
	RC	Ax,d	C = if(carry out of Ax_result ? 1:0)
			Z = if(Ax_result == 0 ? 1:0)
30	<u>Version Specific</u>		
	LL	Ax,n	Z = if(Ax_result == 0 ? 1:0)

The code for an immediate mode instruction, IN Ax, <constant>, is identical to the code for IN Ax, (PC)+, followed by the <constant> value, where the latter value has the size of the x register. In this context, IN stands for LD|ST|AD|SU|AN|OR|EO. The instruction format for LD, ST, AD, SU, AN, OR, EO is shown in Fig. 18, where instr 506 is the instruction field, ax (formerly id) 504 is the addressing mode field for x, ay 503 is the addressing mode field for y, cdn 505 is the condition field and rx, ry 501, 502 are the register fields. The arrangement of the fields in Fig. 19 is with the rx field

-25-

501 at the most significant end. For BR, JS, JI, RI, VS and FN the format is shown in Fig. 20. In this case, the fields corresponding to instr, ay and ax of format 1 are occupied with the codes corresponding to ST 555, "register" 552 and "simple" 553 respectively. The remaining three fields must then be divided up into a part that specifies the instruction 551 and a part which specifies the condition 554. The condition part is the four least significant bits of the combined field. The remaining instructions are termed "manipulate" instructions (MA instructions). The LL instructions is included in this category. Their format is shown in Fig. 21. The number of bits available to code the MA instructions 582 will be a function of WIR and NRE, and the minimum number of bits will be 5. This is sufficient to allow the coding of the instructions from TB to RC in the instruction table above. Surplus bits are used to code the instructions LL, where the number of literals that can be coded will depend on the number of surplus bits available.

20           The fields of the SMILE instruction are coded as follows:

```

instr:
000 LD
25 001 ST
   010 AD
   011 SU
   100 AN
   101 OR
30 110 EO
   111 MA (i.e. the code in the instr field for all the
        manipulate instructions.)

ax:
35 0   Ax = x
   1   Ax = (x)

ay:
40 00  Ay = y
   01  Ay = -(y)
   10  Ay = (y)+
   11  Ay = #(y)

```

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The remaining fields do not have fixed width and so the following specifications must be interpreted according to the number of bits available in a particular application.

```

5   rx and ry:
    000...000      S[0]
    000...001      S[1]
    etc...
    011...111      S[NSR-1]  (=SP)
10  100...000      L[0]      (=SP)
    100...001      L[1]
    etc...
    111...111      L[NLR-1]  (=PC)

15  cdn:
    000  S          if_set("always")
    0001 Sbar       if_not_set("never")
    0010 C          if_carry
    0011 Zbar       if_not_zero
20  0100 Cbar      if_not_carry
    0101 Z          if_zero
    0110 N          if_negative
    0111 V          if_overflow
    1000 Nbar       if_not_negative
25  1001 Vbar      if_not_overflow
    1010 L          if_less(<0)
    1011 Lbar       if_ge(>0)
    1100 1          if_le(<=0)
    1101 M          if_ls (lower/same)
30  1110 Ibar      if_gt (>0)
    1111 Mbar       if_hi (higher)
    control_instr:
    00..000  BR
    00..001  JS
35  00..010  JI
    00..011  RI
    00..100  VS   4
    00..101  VS   5
    etc..
40  11..111  VS   2n-1 (n == width of bit field for
                        control_instr)

```

If application-specific instructions are implemented, then they take the codes of the highest numbered VS codes.

```

ma_instr:

```

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	00..000000	LL	0
	00..000001	LL	1
	00..000010	LL	2
	etc..		
5	11..011111	LL	$2^{n-1} - 32$ (n == width of bit field for ma_instr)
	11..100000	TB	0
	11..100001	TB	1
	11..100010	TB	2
10	11..100011	TB	3
	11..100100	FB	0
	11..100101	FB	1
	11..100110	FB	2
	11..100111	FB	3
15	11..101000	SB	0
	11..101001	SB	1
	11..101010	SB	2
	11..101011	SB	3
	11..101100	CB	0
20	11..101101	CB	1
	11..101110	CB	2
	11..101111	CB	3
	11..110000	SL	1
	11..110001	SR	1
25	11..110010	RL	1
	11..110011	RR	1
	11..110100	SL	2
	11..110101	SR	2
	11..110110	RL	2
30	11..110111	RR	2
	11..111000	SL	4
	11..111001	SR	4
	11..111010	RL	4
	11..111011	RR	4
35	11..111100	SA	1
	11..111101	SA	2
	11..111110	RC	L
	11..111111	RC	R

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## Claims

1. A microprocessor for executing byte compiled Java code in hardware comprising:
  - 5 a RISC processor;
  - a Java module to execute a first set of Java instructions in the RISC processor;
  - a RISC module to execute a second set of Java instructions as microcode in the RISC processor, said
  - 10 RISC module including means for handling interrupts and a flexible hardware interface to control highly specialized peripheral devices; and
  - a datapath in the RISC processor shared by both modules, said datapath including a register file shared
  - 15 by both modules, said register file having a plurality of elements shared by the Java module and the RISC module, the Java module seeing a first portion of the plurality of elements as a circular Java operand stack and a remaining portion of the plurality of elements as storage
  - 20 registers, the RISC module seeing the plurality of elements as a register file.
2. The microprocessor of claim 1 wherein the register
- 25 file includes a control bit for tracking which module is in operation.
3. The microprocessor of claim 1 wherein the register
- 30 file includes a program counter containing the address of an instruction to be executed.
4. The microprocessor of claim 1 wherein the register
- 35 file includes a program counter base register for storing the address of a new method to be invoked.

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5. The microprocessor of claim 1 wherein the register file includes a local variable base address to store base address information for local variables in a Java method.

5

6. The microprocessor of claim 1 wherein the register file includes a Java stack pointer to track a location of the top of the Java operand stack.

10

7. The microprocessor of claim 1 wherein the register file includes a RISC stack pointer to point to a location where the RISC can temporarily store variables if the register file is full.

15

8. The microprocessor of claim 1 wherein the register file includes a status register having a pair of status bits that inform the RISC module to use a value of the top of the JAVA operand stack as a register operand when executing a Java instruction, each of the pair of status bits controlling an source or a destination operand.

20

9. The microprocessor of claim 8 wherein when the status bits are set, the RISC module disregards the source or destination operand and uses the contents of a predefined register as the source or destination operand.

30

10. The microprocessor of claim 8 wherein the status bits are set and cleared by a RISC program that replaces the Java instruction.

35

11. The microprocessor of claim 1 wherein the RISC processor has a SMILE RISC architecture.

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12. The microprocessor of claim 1 wherein a control bit is located in a status register that is located outside of the register file.

5

13. A method of executing Java code in a RISC processor, said method comprising:

executing a first set of Java instructions in the processor with a Java module,

10       executing a second set of Java instructions in the RISC processor with a RISC module, the second set being more complex than the first set;

interrupting the processor when an instruction too complex for execution by the Java module appears;

15       executing the complex instruction separately from other instructions in the RISC module; and

returning to the Java module when the RISC module has finished executing the complex instruction.

20

14. The method of claim 13 wherein the interrupting the processor includes:

confirming that a set of implementation specific conditions require the processor to be  
25 interrupted;

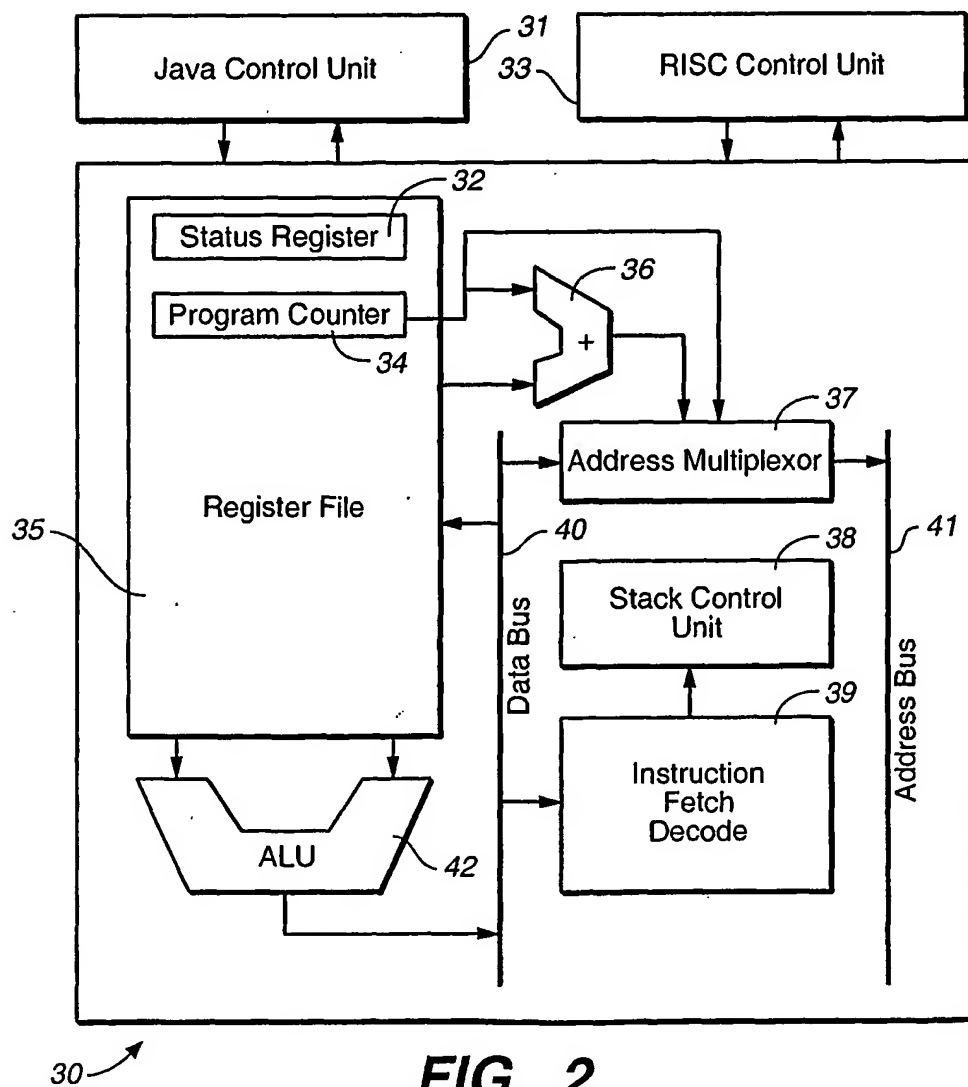
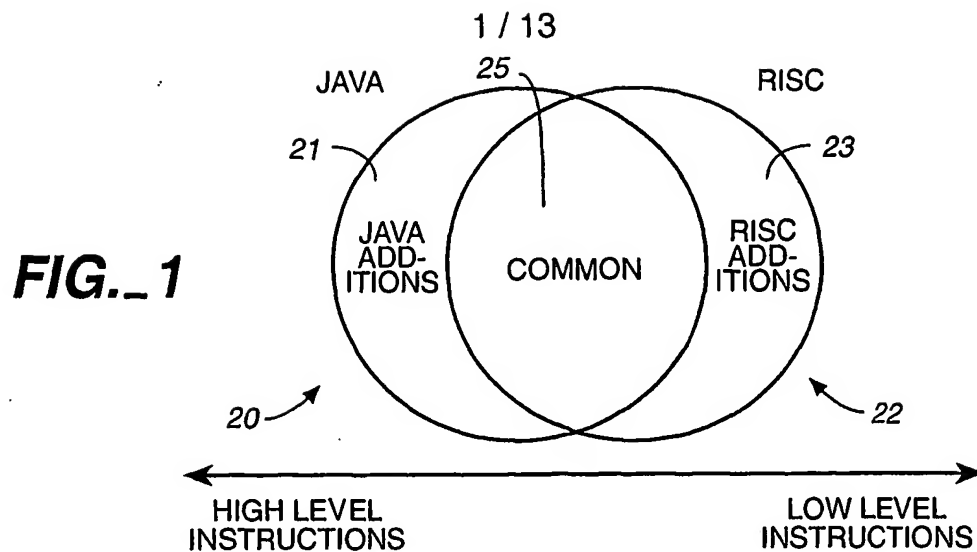
storing a return address on the top of a stack in the RISC module;

jumping to a predefined address and reading a new branch address;

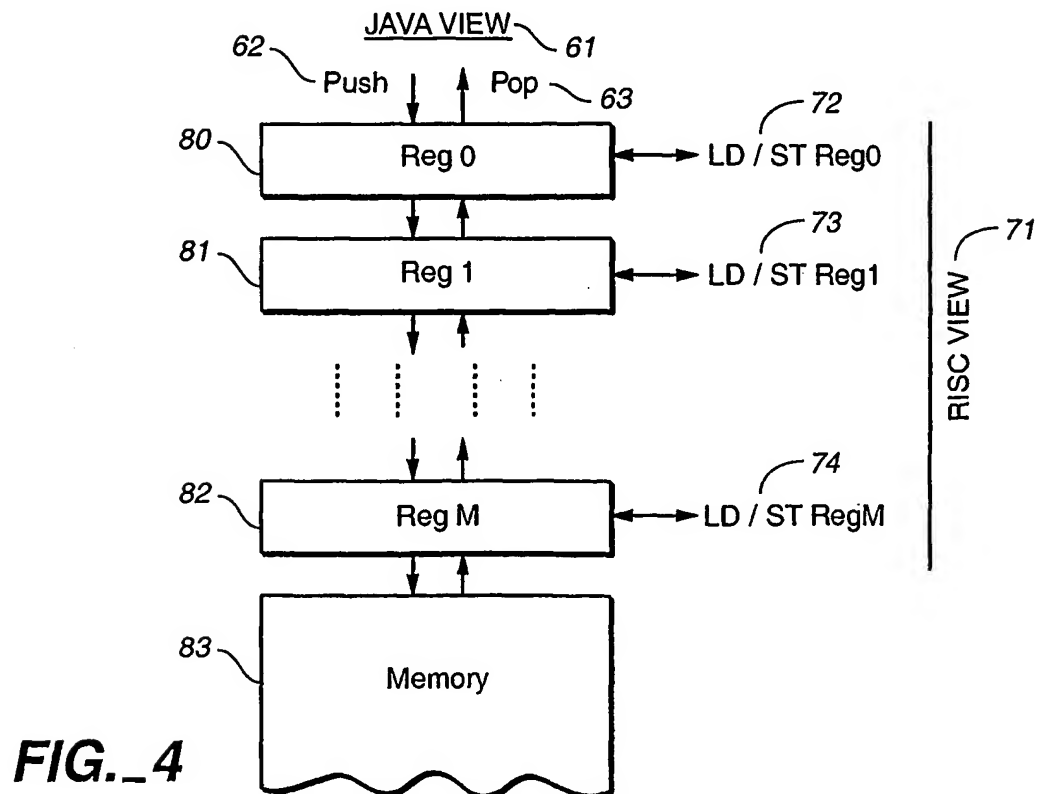
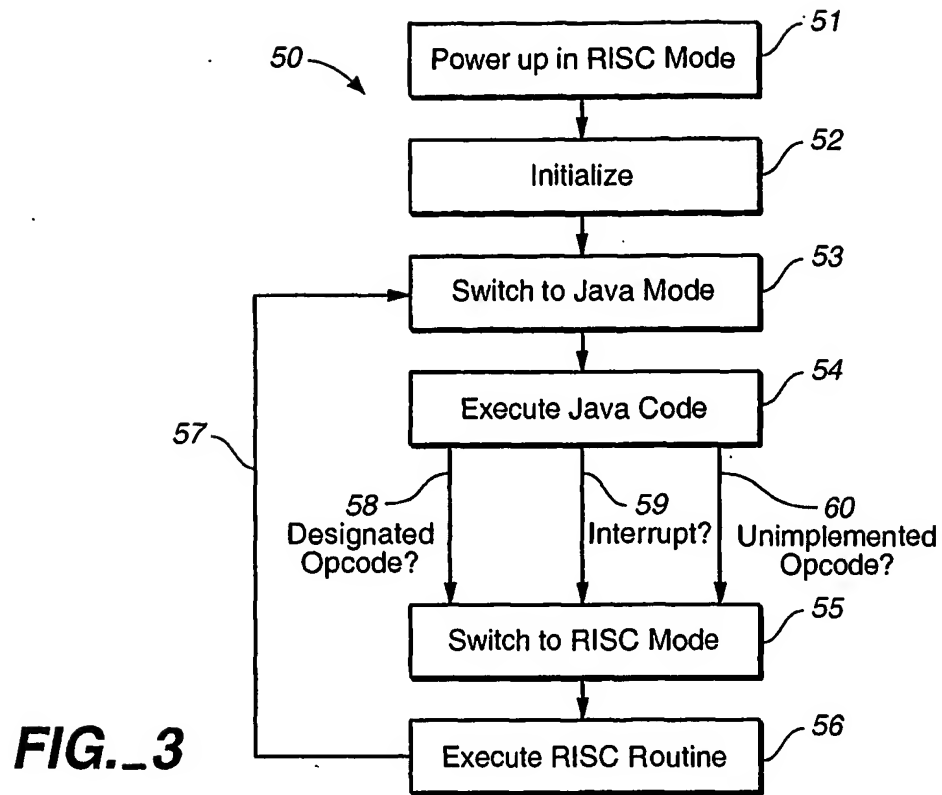
30       executing a branch instruction to the new branch address in the RISC module; and

executing a return instruction to return to program execution using the Java module.



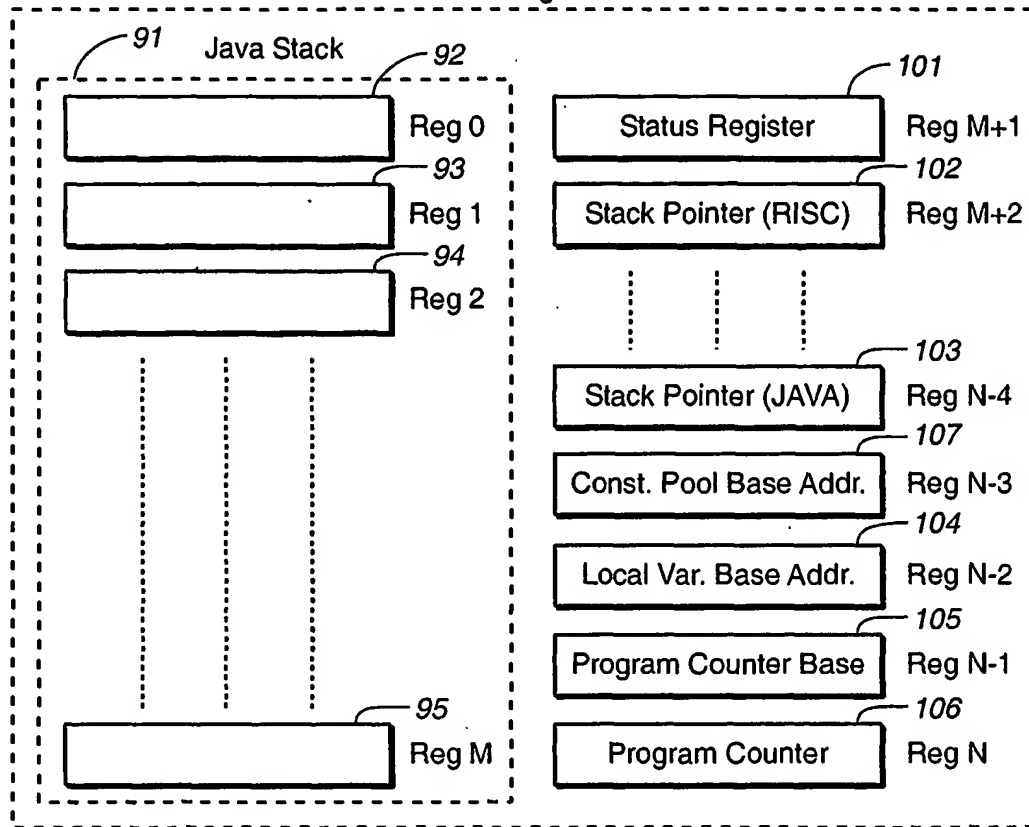


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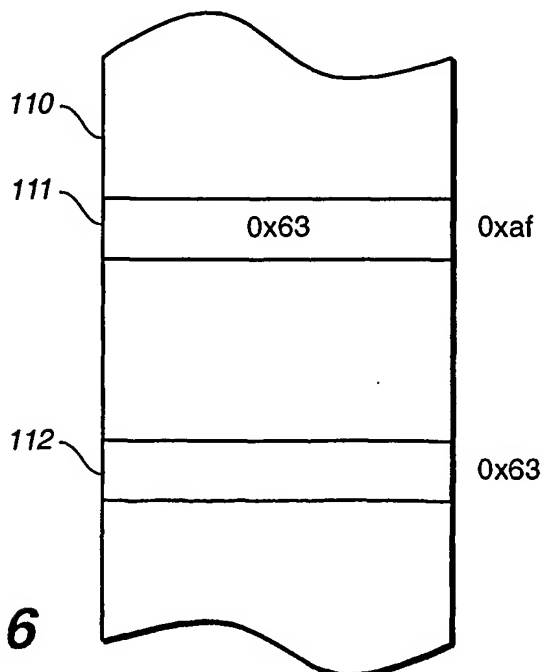


90

RISC Registers

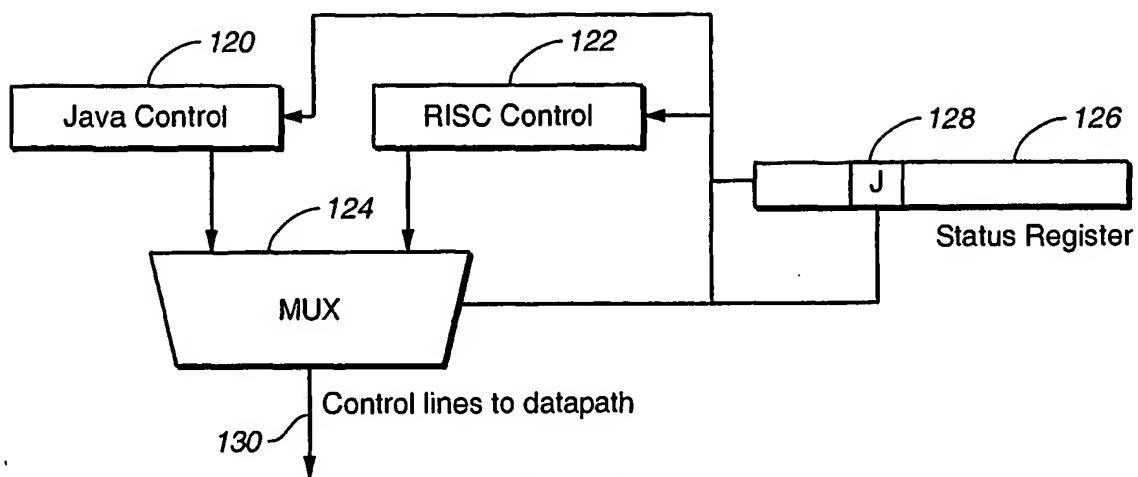
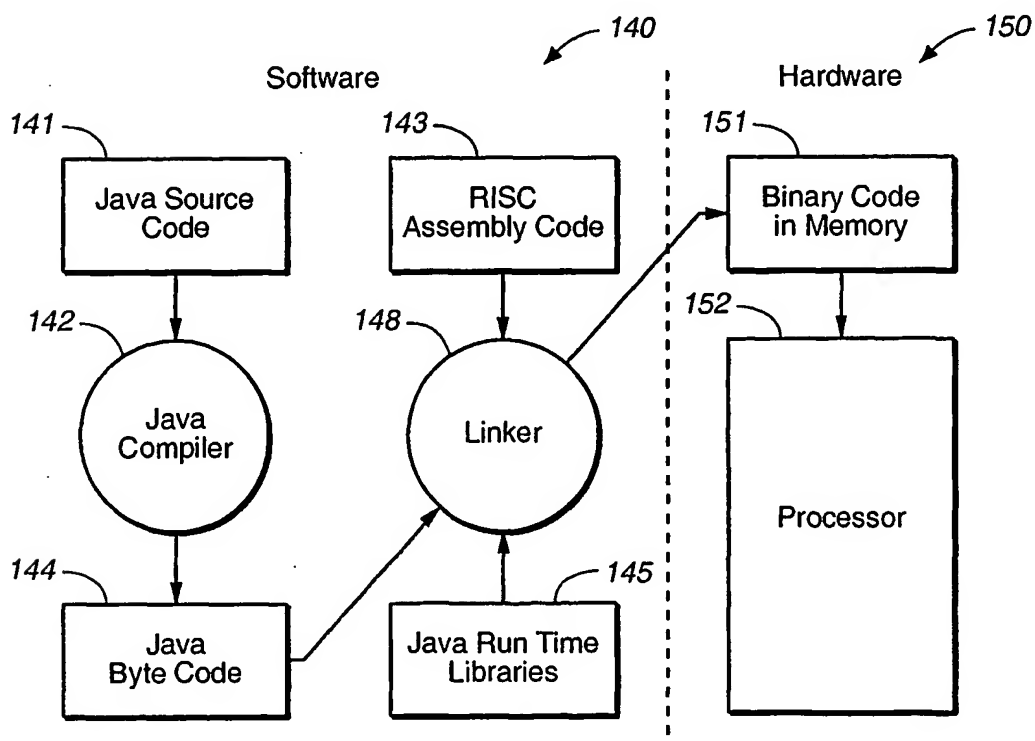


**FIG.\_5**

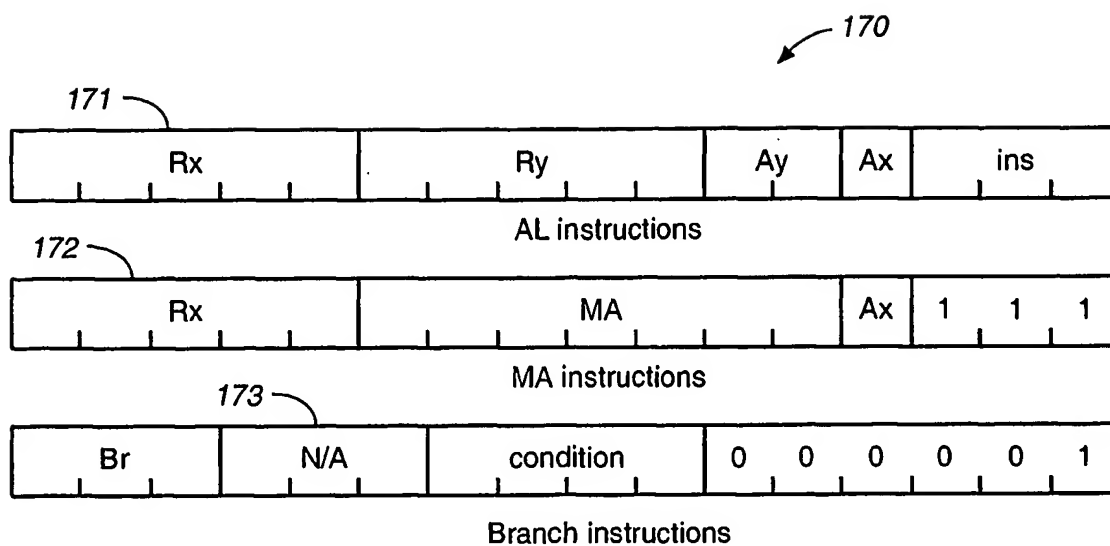
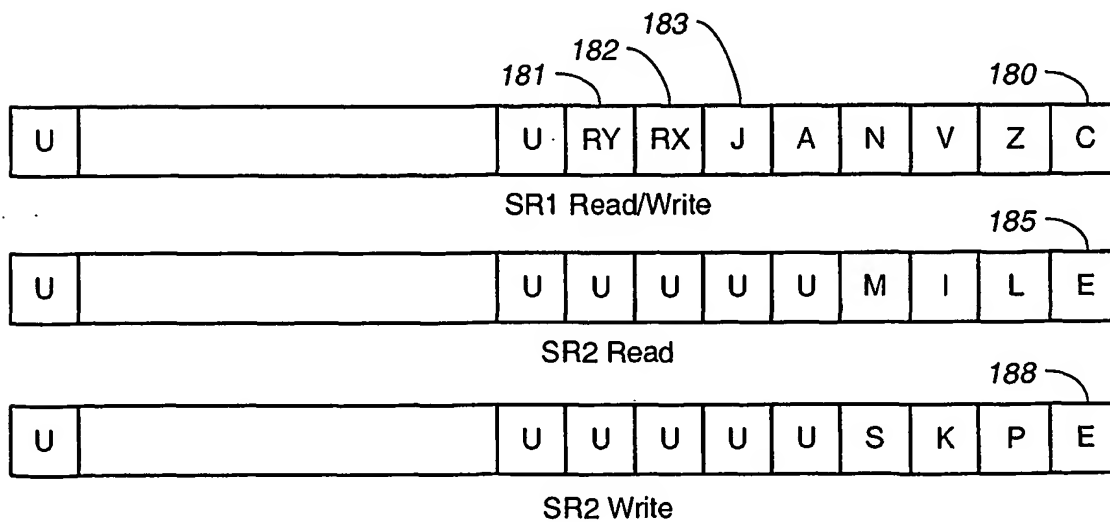


**FIG.\_6**

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**FIG. 7****FIG. 8**

5 / 13

**FIG. 9****FIG. 10**

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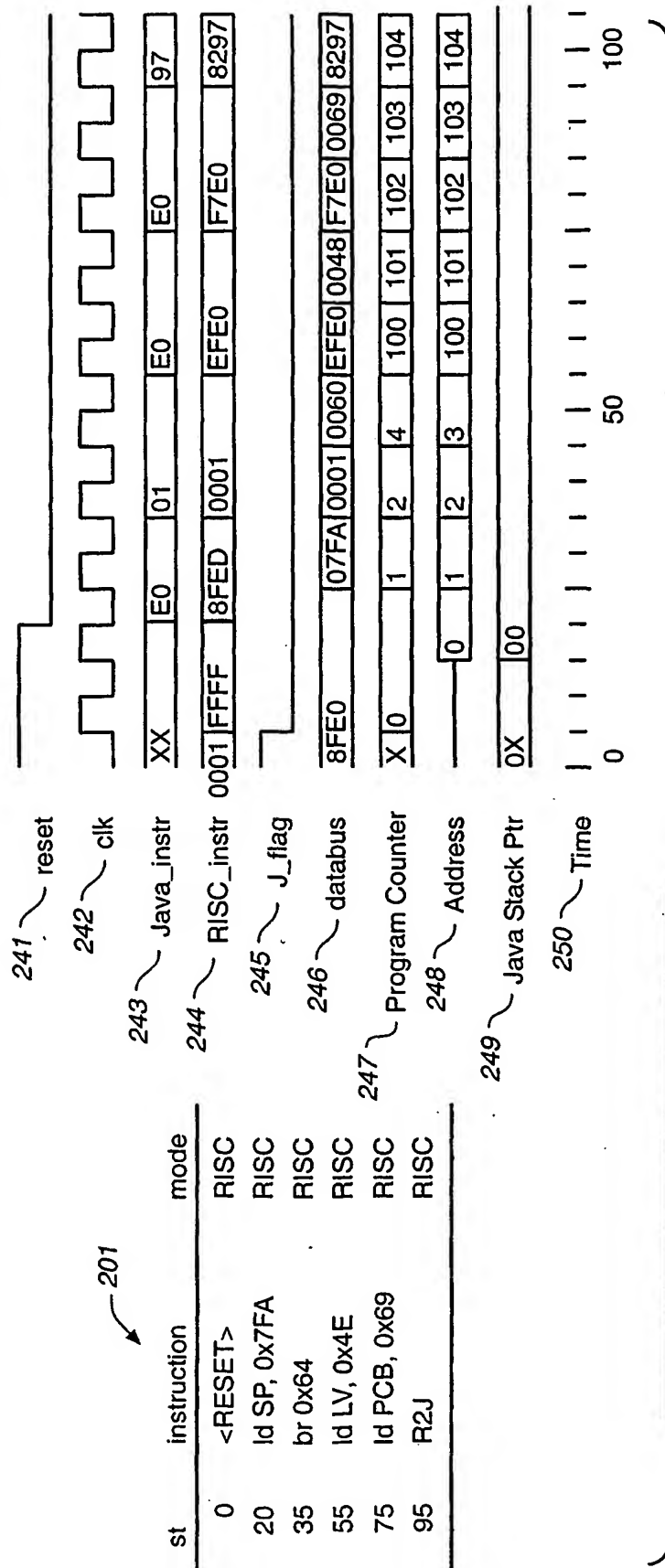


FIG. 11

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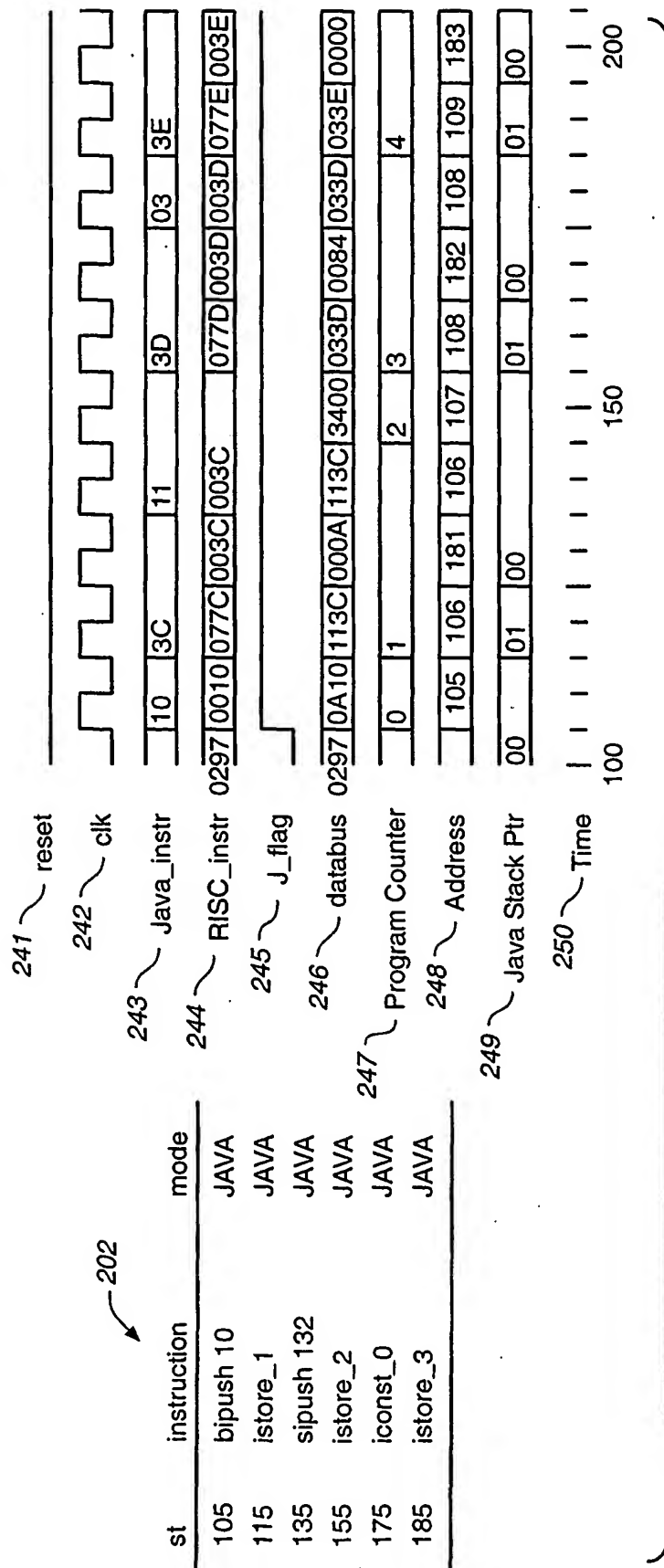


FIG.-12

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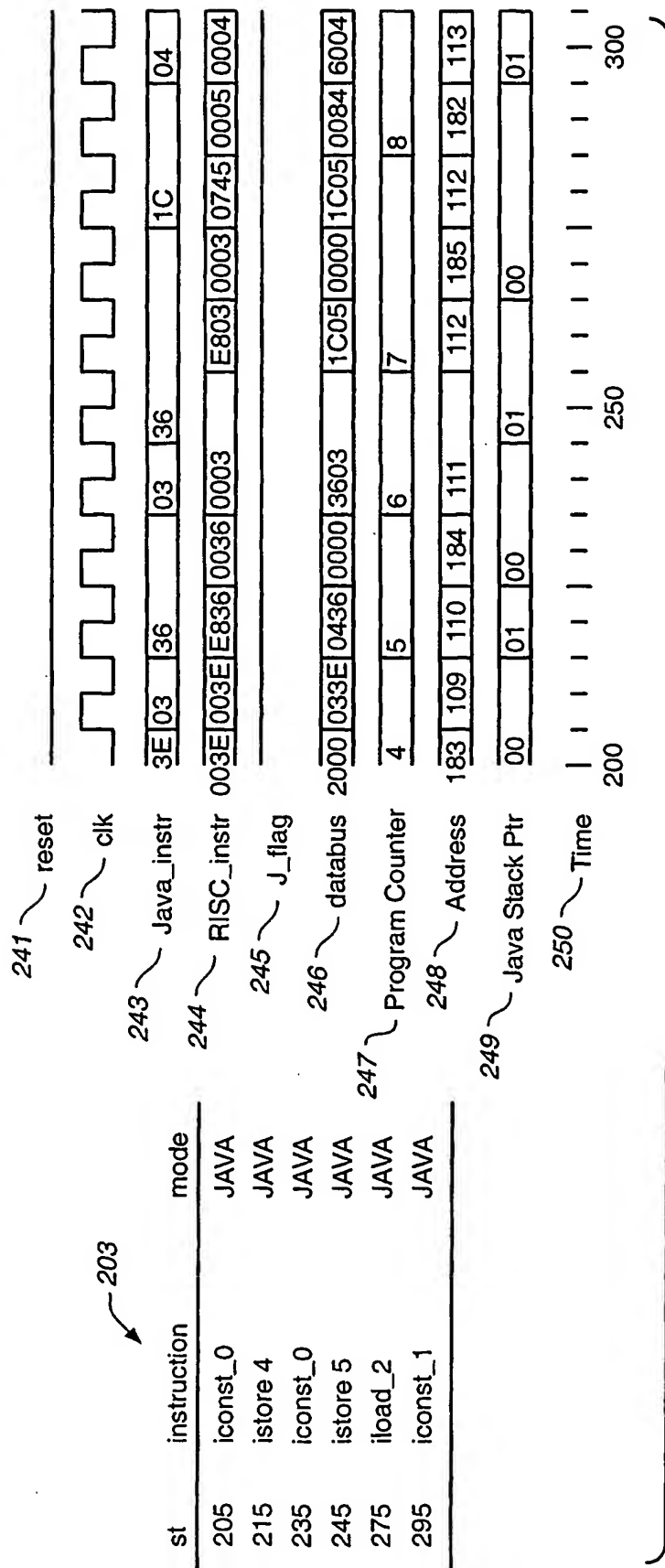


FIG. 13



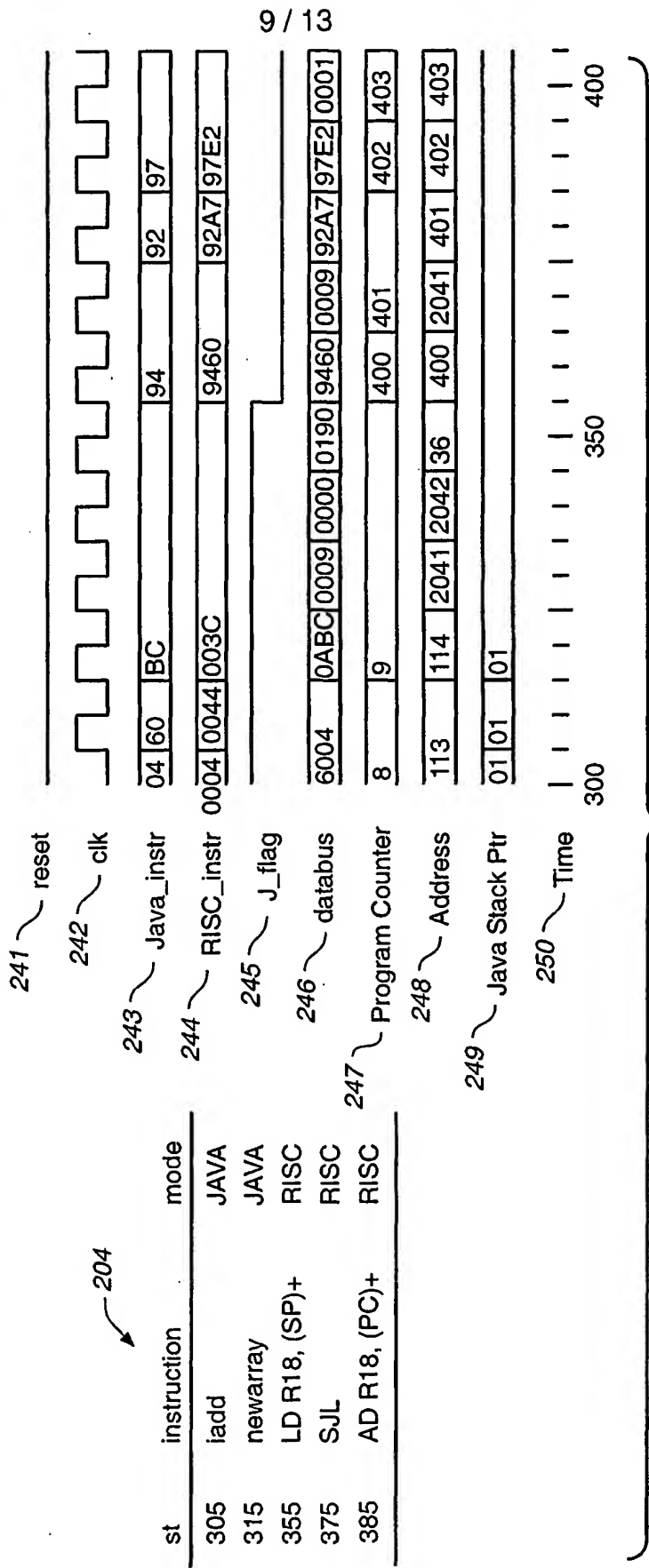


FIG.\_14

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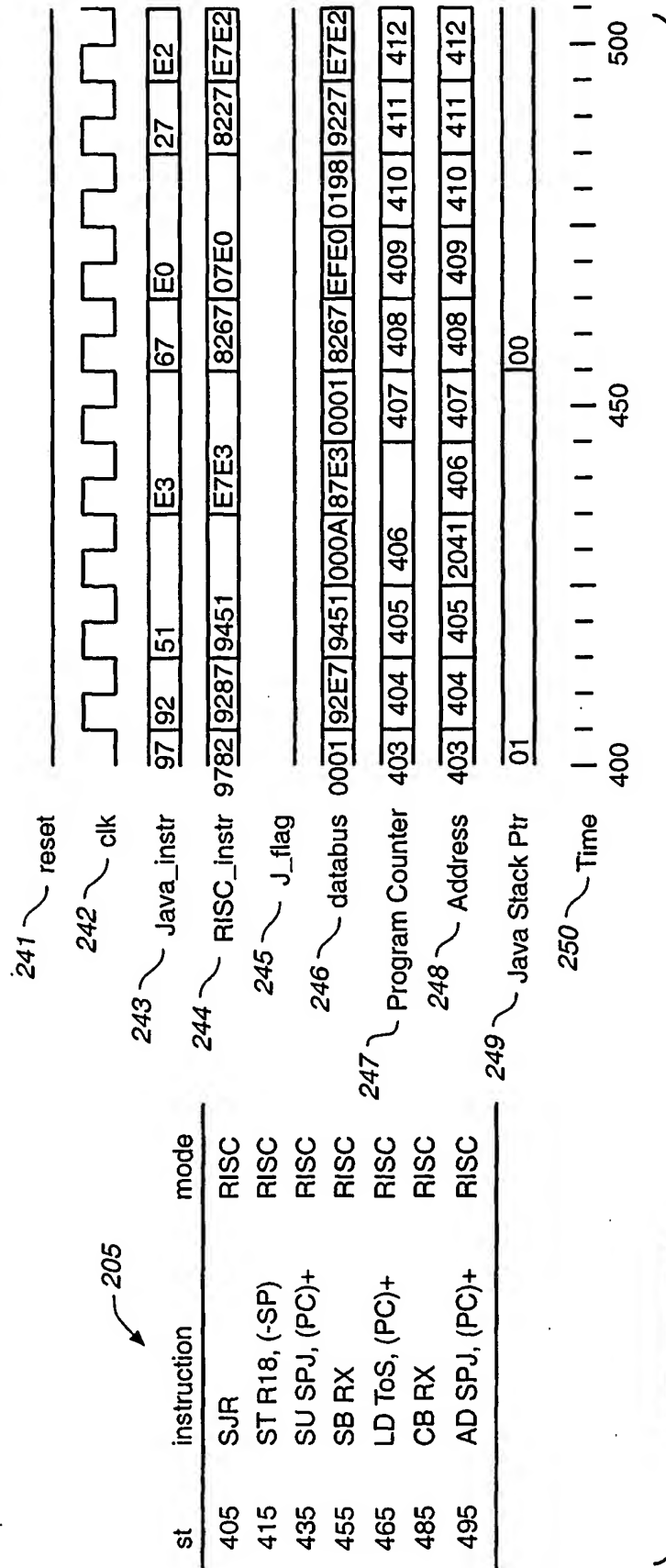


FIG. 15

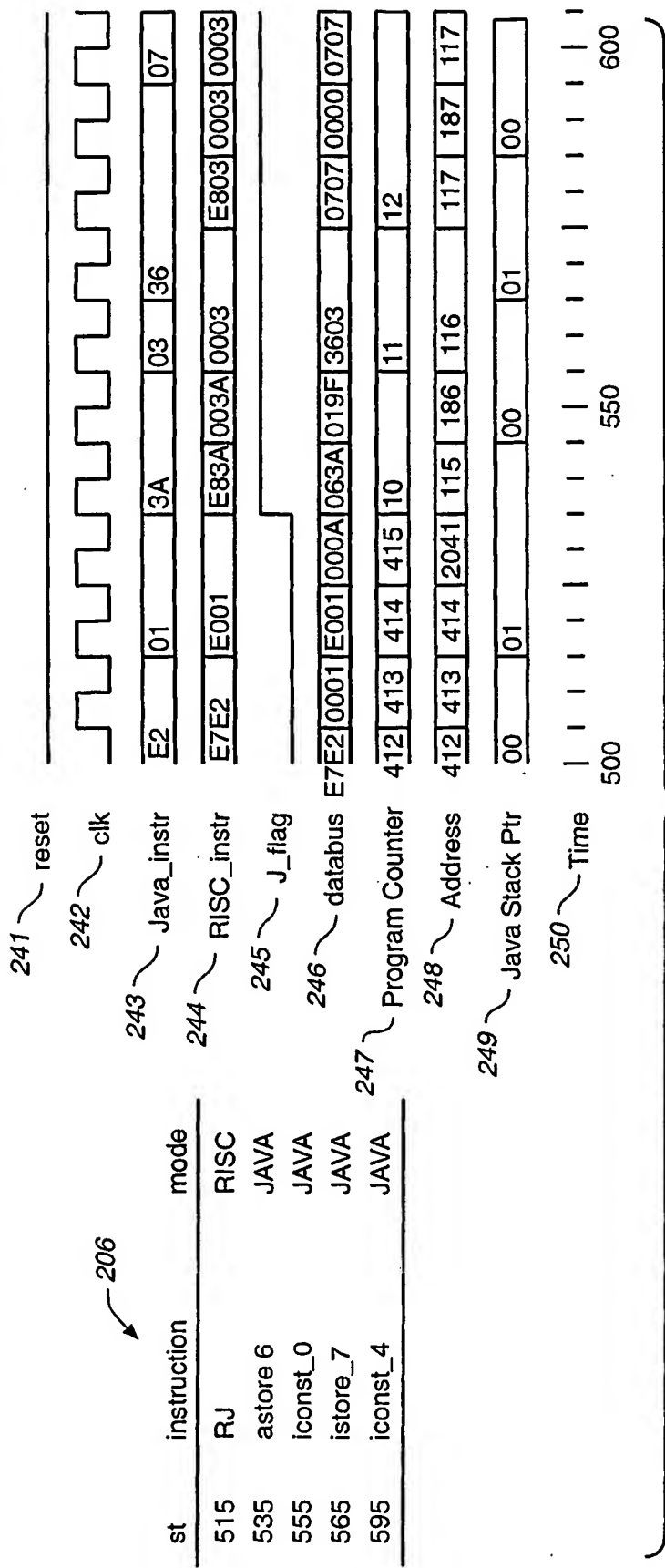
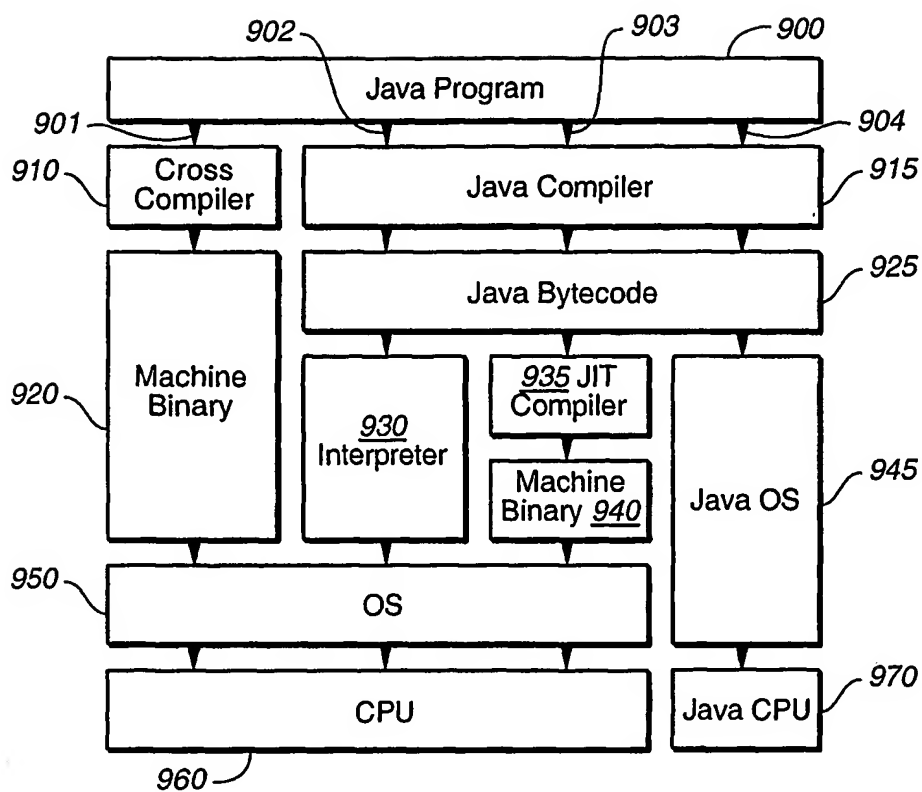
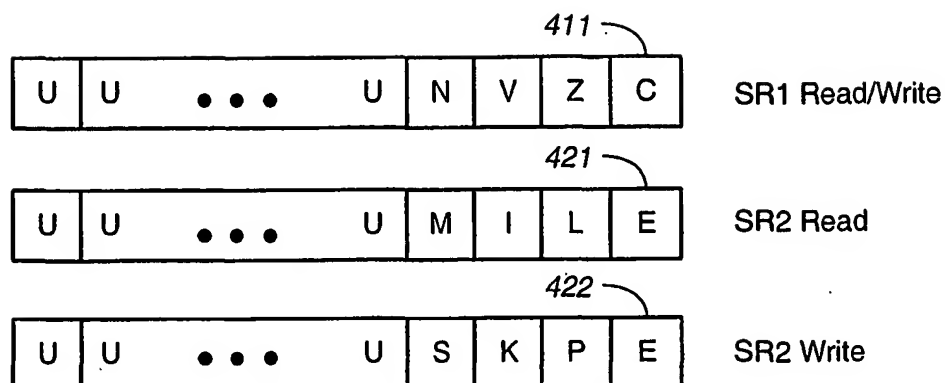


FIG.\_16

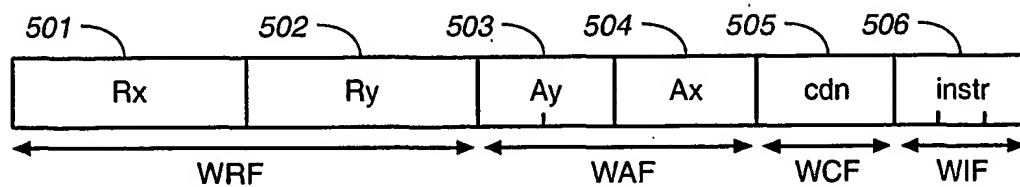
12 / 13



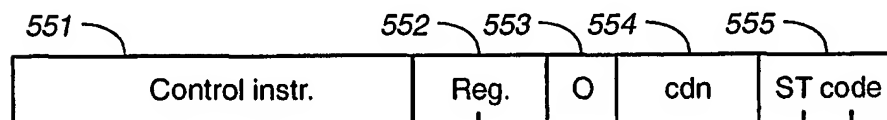
**FIG. 17**  
(PRIOR ART)



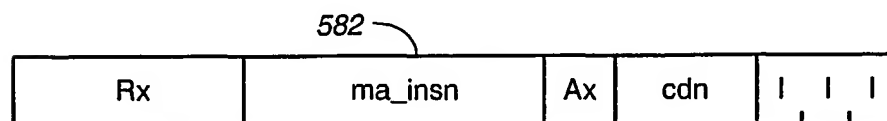
**FIG.\_18**



**FIG.\_19**



**FIG.\_20**



**FIG.\_21**